AUDIO-VISUAL AND HYDROACOUSTIC OBSERVATIONS OF THE DEAD SEA CALIBRATION EXPERIMENT

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ABSTRACT

Three chemical charges of 500, 2060 and 5000 kg were detonated in November, 1999 in the Dead Sea at water depth of about 70 m (480 m below the ocean level). The main objective of the experiment was to calibrate the seismic travel times at local and regional distances.

Using a specially designed recording system and GPS measurements, it was possible to provide an accuracy of 5 milliseconds for the detonation time and few meters for the location. However, the actual location accuracy was reduced to 50 meters due to strong variable undercurrents and winds in the Dead Sea.

The source parameters of the explosions are:

Date	Origin Time (GMT)	Coordinates	Charge, kg	Magnitude	
				M_L	m_b
08.11.99	13:00:00.330	31°31'58.804"N 35°26'26.242"E	500	3.1	-
10.11.99	13:59:58.210	31°32'01.800"N 35°26'24.000"E	2060	3.6	-
11.11.99	15:00:00.795	31°32'00.995"N 35°26'28.760"E	5000	3.9	4.1

(Note: The GII is not estimating m_b magnitudes for event of m_b<4.0)

The experiment was video taped. The video and audio tracks provide a “live” presentation of interesting effects such as the “cavitation hat”, arrivals of the shock waves and the bubble pulsations at the raft, where the camera was placed, and water uplift at the detonation point. The video clips also provide a rough estimation of the shock wave propagation time to the surface and to the raft and contribute to verification of the charge depth and explosion-to-raft distance.

One of the main objectives of the explosions was to characterize the specific seismic source by observation of radiated energy in the close vicinity. Two piezoelectric sensors, located at a distance of about 700 m from the shot point and at water depth of 25-30 m, provided unique pressure measurements of the water shock waves. The measured peak pressures significantly exceeded the expected values from an equal TNT charge in ocean water due to enhanced acoustic impedance of the supersaline Dead Sea water. Analysis of different phases and arrival times on the records provided identification of surface (“ghost”) and bottom reflections and contributed to the verification of the experiment configuration. The shock wave energy was calculated utilizing the wave energy flux density equation, recorded pressure-time functions and unusual properties (density and acoustic velocity) of the Dead Sea water. The energy percentage was estimated relative to the energy of the explosive material used in the experiment.

This is not the first time that explosions have been carried out in the Dead Sea; it is, however, the first time that a seismic source with an equivalent magnitude of about 4.0 on the Richter scale has been artificially generated in the area. Unique observations of underwater shot phenomena and shock waves in the particular Dead Sea water were obtained. The experiment is also unique for this region since it has precise information on coordinates and origin time of an explosion being recorded over 2500 km beyond the borders of Israel.

Key Words: Dead Sea, underwater explosion, travel time calibration, audio-video clip, water shock wave

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OBJECTIVE

The overall objective of the Dead Sea explosions was to calibrate the seismic travel times at local and regional distances in the Middle East and East Mediterranean region, to calibrate regional and IMS stations and provide data for the improvement of the CTBT monitoring capabilities with the IMS.
The specific objectives of the presented research relate to quantifying the coupling and the specific seismic source characterization of the explosions, including analysis of audio and video recordings, observation of radiated energy in close vicinity and measuring shock wave pressure in the unique Dead Sea settings.

RESEARCH ACCOMPLISHED

1. Charge design and detonation technique. Based on results of preliminary small test explosions of 25 kg at depths 70-100 m, it was decided to use a combined detonation technique: electric fuses and detonating cord (fuse) with multiple initiation points, and to limit the charges to the depth of 70 m. Parameters of the explosions are presented in Table 1. The charge unit design is shown on Figure 1. Sample photographs of the charges are presented in Figure 2. The primer blasting agent, CHEN AMON explosive, based on Ammonium Nitrate, has density 1.3-1.4 gr/cm^3, which is higher than the Dead Sea water density 1.236 gr/cm^3 (Anati, 1997), and detonation velocity 5500 m/sec. The Rotex detonating fuse (cord) 10,5 was used, which detonates at a velocity higher than 6500 m/sec.

2. Measurement of origin times and coordinates. In the first shot, a small seismic sensor was attached to the charge and provided accurate determination of the origin time. During the second shot, the sensor got disconnected from the recording system, and the O.T. estimation is based on measuring the relative propagation time of shock waves to piezoelectric sensors (see Chapter 4 below) and the absolute GPS time of the waves arrival to a hydrophone, co-located with the sensors. For the largest explosion we recorded the exact moment of detonating electric fuses, connected to detonating cord, which initiated the charge. The finite detonation time of the cord of the length of about 70-75 m is estimated to be 10 msec (~ 70m/7000m/sec), was also considered. The timing in the recording system was continuously synchronized with GPS. Using 500 samples per second digitizer, we obtain accuracy better than 5 msec.

The differential GPS system "Magellan" provided an accuracy of few meters in determining the location coordinates. Nevertheless, due to strong variable underwater currents and winds in the Dead Sea (especially during the second shot), we estimate the actual accuracy to be about 50 m, corresponding to possible drifting of the charge around the anchor.

Table 1. Parameters of the calibration underwater explosions in the Dead Sea, charge depth H=70-73m, the sea depth ~260 m (Ground Truth Information rank GT0).

Date	Origin time (O.T.), GMT	Location, GPS Magellan	Total charge kg	Charge components, kg			Initiation of the charge (using electric fuse - EF, and detonating cord - DC)	Comments
				chen amon	Accelerator			
					Red chen	TNT +PETN		
08.11	13:00:00.33	31.5330N 35.4406E	500	410	60	30	EF connected to DC on the water surface and at depth near the charge	
10.11	13:59:58.21	31.5338N 35.4400E	2060	1640	240	180	EF connected to DC (length about 70-75 m) on the water surface	After detonation failure on 9.11, two additional TNT units were submerged (10.11) near the main charge
11.11	15:00:00.80	31.5336N 35.4413E	5000	4460	360	180	EF connected to DC (length about 70-75 m) on the water surface	An impressive water uplift about 15 m was observed 5-7 sec after the detonation

3. Audio-visual records of the explosions. The experiment was video taped. A home camera was placed on the raft that was hosting all measurement equipment and the initiation systems, at a distance of several hundred meters from the shots. The video and audio tracks provided observations and rough time measurements of interesting physical phenomena, such as a "cavitation hat", arrivals of the shock waves and the bubble pulsations near the raft. The video clips also provided a rough estimation of the shock wave propagation time to the surface and to the raft and contribute to verification of the charge depth and explosion-to-raft distance.

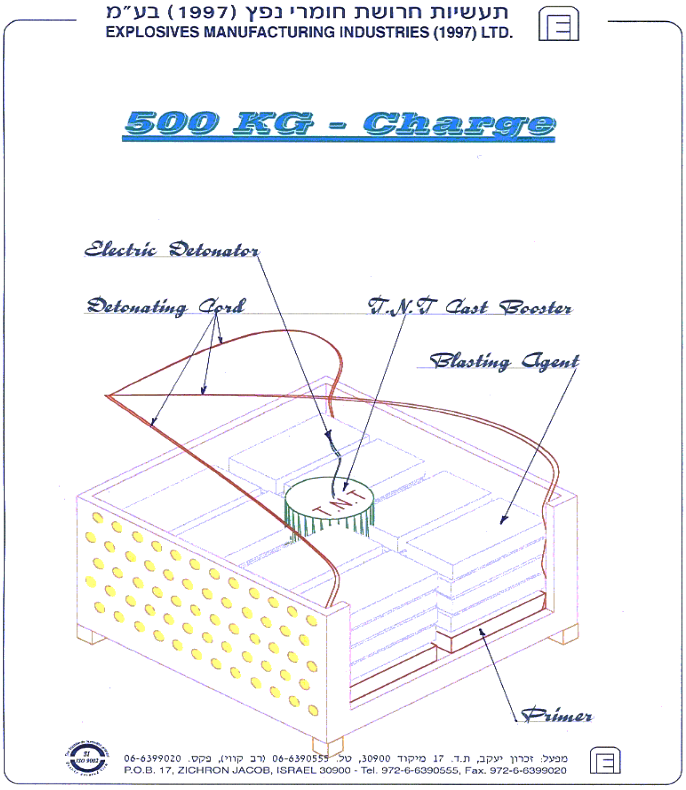

Fig. 1. Design of the charge unit, containing 500 kg of explosives for the explosion on 8.11.99 and 10.11.99 (total of 4 units), and 833 kg for 11.11.99 (total of 6 units).

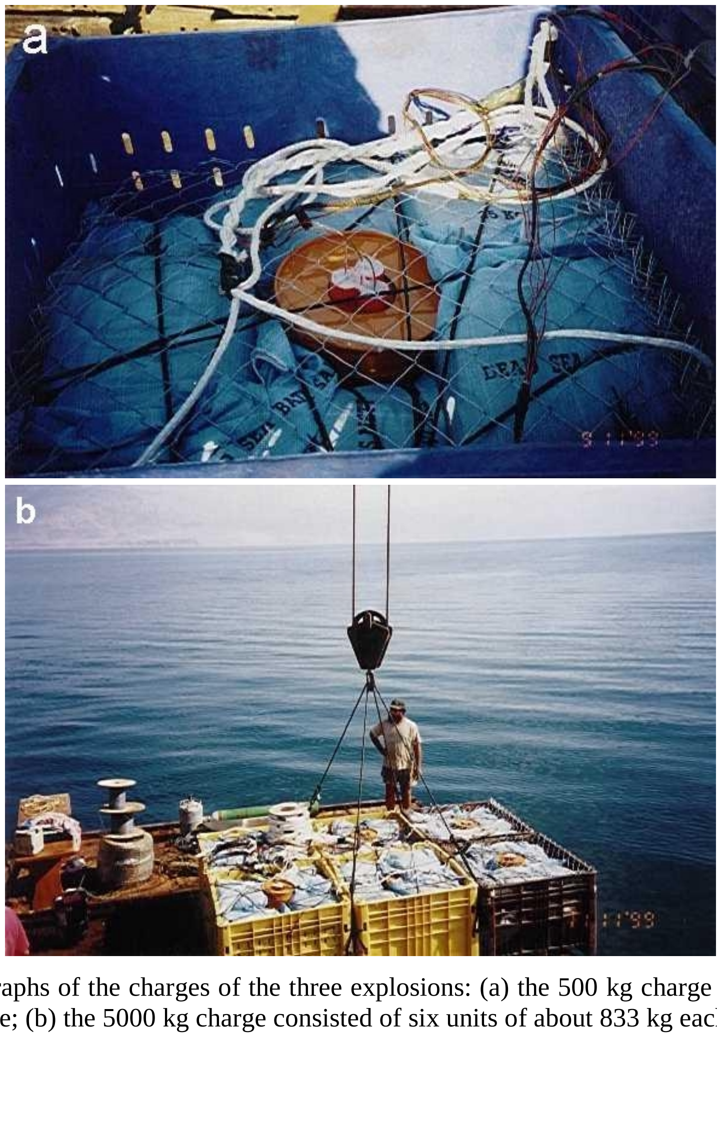

Fig. 2. Sample photographs of the charges of the three explosions: (a) the 500 kg charge unit was used also for the 2060 kg charge; (b) the 5000 kg charge consisted of six units of about 833 kg each.

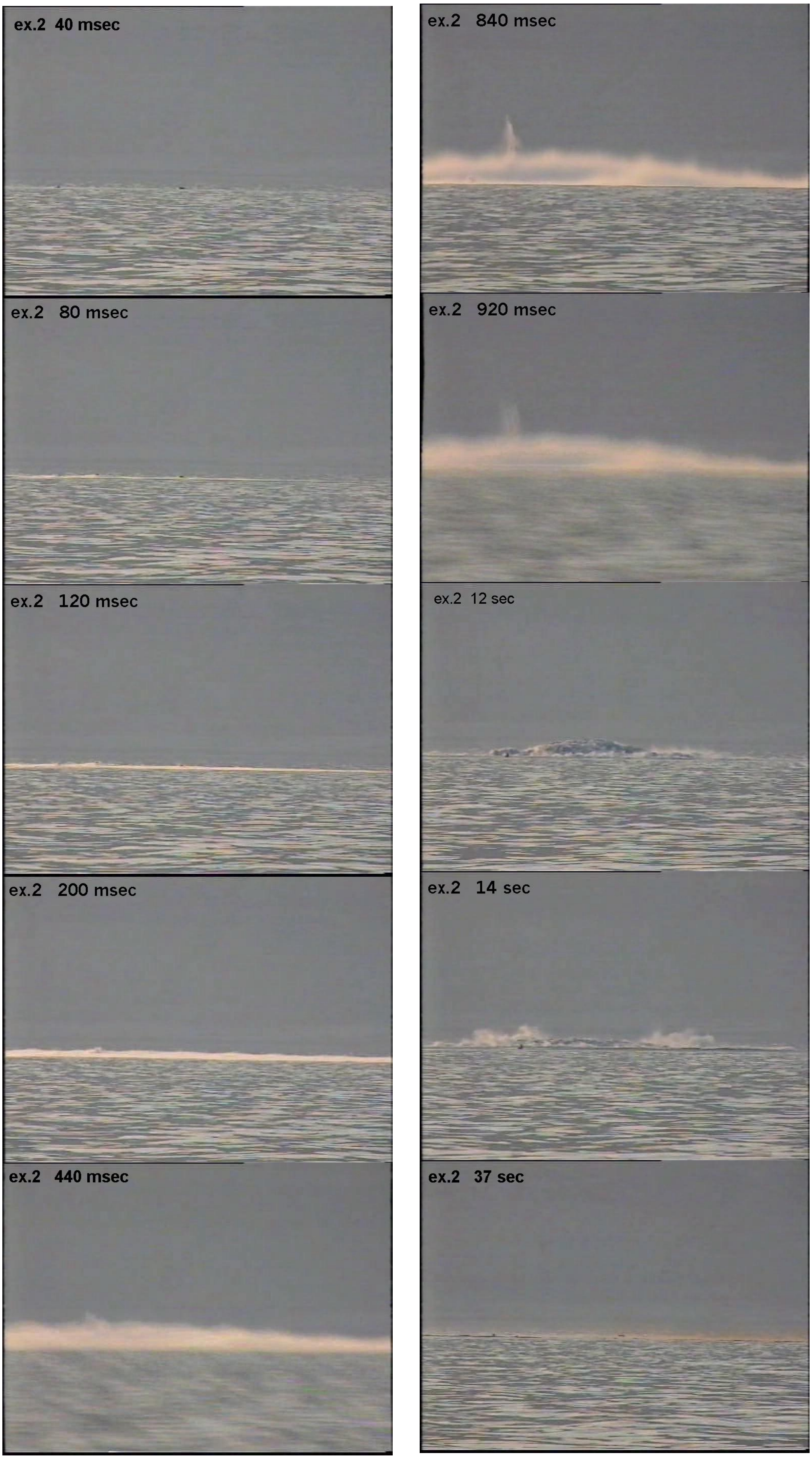

Fig.3. Snapshots from the video-record of the 2060 kg explosion

The video-recording rate is 25 fps (frames per second). This rate facilitates time measurement accuracy of about 40 msec. Figure 3 shows snapshots of the 2060 kg explosion, where following phenomena can be observed:

a) "Cavitation hat", created when the direct shock wave arrivals to the water surface. An initial sign of the cavitation strip can be revealed at about 40 msec after initiation, ant this estimation fits well the propagation time t_c = 70m/1770m/s = 0.0395 sec. The frames 80, 120 and 200 msec show an evolution of the cavitation process;

b) The camera went out of focus by the shock wave impact upon the raft at about 440 msec after detonation, yielding an estimation that the raft distance from the shot is ~775 m. This estimation corresponds well to the estimation obtained from hydroacoustic recordings (see Table 3);

c) The focus' distortion is repeated after ~0.5 sec (at the 920 msec snapshot) due to the gas bubble pulsation, which is close to the predicted and measured from seismic spectra bubble pulse period (Table 3);

d) Water uplift by the gases rise, in the time window 9-14 sec;

e) Appearance of yellow gases – explosive's detonation products, during 35-40 sec, in the area displaced to the right from the epicenter. These displaced gases are also an evidence to the strong underwater currents in the Dead Sea, which prevented location accuracy better than 50 m of the charge .

The video-record of the largest explosion 5000 kg has the impressive audio-track providing several specific audible signals, produced by the gas bubble pulsation, with intervals little less than 1.0 sec. It corresponds well to the estimation made from seismic records, of the bubble pulse period of about 0.8 sec (Table 3).

15 sec. videoclip of the 5000 kg shot

ex3_15sec.mpg

4. Types of water shock waves. The water pressures were measured by Sadwin Engineering Consultancy using type 138A01 piezoelectric underwater blast sensors manufactured by PCB Piezotronics. The pressure-time history was recorded by a computer system with 250 kHz response for each channel used. The record duration was only 0.7 sec due to some restrictions of computer memory and disc space. The full record of the largest explosion is plotted on Fig.4. The measurement gage was located at the distance of about 600 m and at the depth of 30 m.

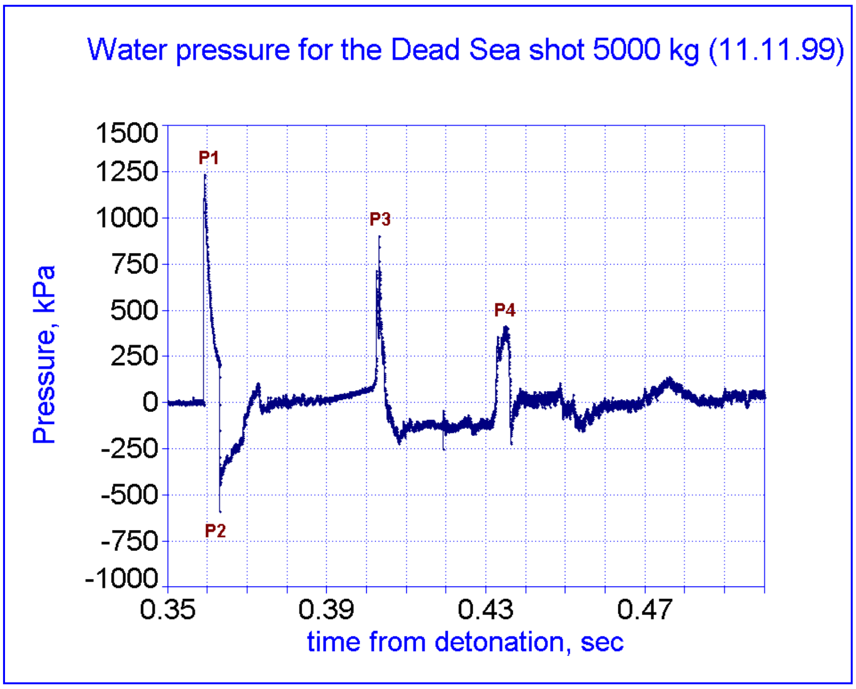

Fig.4. Pressure-time history of the largest explosion.

The primary or direct wave P1, and surface-reflected P2 waves can be easily identified, whereas interpretation of P3 and P4 phases meets some difficulties discussed in Chapter 5 below.

The cepstral simulation and inversion algorithm for analysis of regional seismic recordings of underwater explosions (Baumgardt, 2000) allows to separate out the band modulation of the surface reflection, yielding a negative cepstral peak at about 0.15 seconds period from the narrow band (20 Hz) EIL and MRNI seismic data of the Dead Sea shots. The optimal search inversions program returned very low values of the best matching reflection coefficient, sometimes on the order of -0.3 to -0.4 (D. Baumgardt, personal communication), which corresponds in some way to the water pressure measurements (Fig.4) showing the amplitude of the surface reflected wave about half of that of the primary shock wave amplitude.

The acoustic velocity in the Dead Sea has a high value C_w = 1770.6 m/sec (Anati, 1997), supporting the interpretation that the 0.15 sec cepstral peak is caused by the surface reflection. The fundamental frequency in this case is $f_r = C_w /(4*h) = 1770.6/(4*70) = 6.32$Hz, and period is 0.158 sec, fitting well to the cepstral peak. In the ISN spectra, this surface reflection maximum is merged with the 5^{th} harmonic of the bubble fundamental frequency $f_{b5} = f_b * 5 = 1.28 * 5 = 6.4$ Hz, causing enhanced maximums at about 6.46 Hz.

5. Verification of distances and depths. Based on the experiment configuration and arrival times of different phases measured from recordings of the shock waves, we tried to verify estimations of the source-sensor distance r, charge depth h and sea depth H in the shot point area. Travel times of different phases as measured from recordings of piezoelectric sensors and auxiliary hydrophones (which allowed kinematic estimations only) are presented in Table 2.

Table 2. Arrival (travel) times of different water shock waves.

Charge, kg	Sensor type	Sensor depth, h_s, m	Arrival time from the initiation moment, sec					
			Direct wave P1, t_d	Surface reflected P2, t_s	P3 t_3	P4 t_4	1^{st} bubble pulse	2^{nd} bubble pulse
500	hydroph.	2	0.510	-	-	-	0.931	1.289
2060	hydroph.	2	-	-	-	-	1.095	1.602
	piezoel.	30	0.44546	0.44854	-	-	-	-
		25	0.45933	046180	-	-	-	-
5000	hydroph.	2	0.349*	-	-	-	1.147	1.922
	piezoel.	30	0.35915	0.36304	0.40248	0.432	-	-

* - time from the charge detonation moment

The required parameters were estimated from combinations of simple kinematic equations, under the assumption that the shock wave velocity is constant along the whole propagation path (C_w = 1770.6 m/s):

$$r_i/C_w = t_i - \Delta t \qquad (1)$$

where index *i* corresponds to different waves, r_i is the propagation path and depends on ***h*** and ***H***, t_i is the arrival time (relative the initiation moment), and Δt is a delay of a shot caused by the detonation cord with unknown length and detonation velocity (>6500 m/sec), which connects the initiation point on the water surface and the charge at depth.

The detailed bathymetric map of the Dead Sea (Hall, 1993) shows (see Fig. 5), that the sea depth in the experiment area is ***H***=260-265 m.

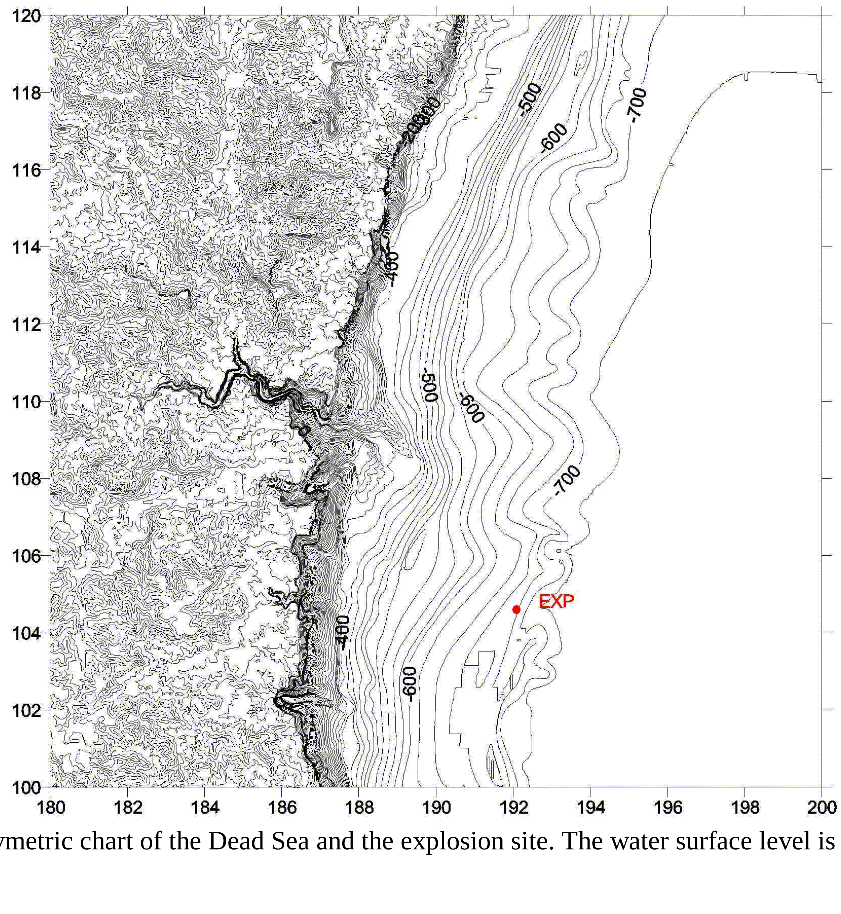

Fig.5. Bathymetric chart of the Dead Sea and the explosion site. The water surface level is -415 m.

The phase analysis results can be summarized as follows:

1. For both shots 2 and 3 the estimated delay Δt is 0.010 sec, a reasonable value considering the detonation cord length of about 70-75 m and detonation velocity 7000-7500 m/s. It is confirmed by a similar time difference of the direct wave arrivals to the hydrophone and the piezoelectric sensors during shot 3 (see Table 2).
2. The interpretation of phase P3 (see also Fig. 6) as the bottom-transmitted wave and P4 as the bottom-reflected wave, provides the sea depth estimate ***H***=265 m, which corresponds well to the batymetric map estimation. However, the very high amplitudes and short duration of phase P3 contradict the theoretical description of the bottom-transmitted wave as a slow-raising and low amplitude wave, and correspond much better to the bottom-reflected wave (see, for example, USACE, 1991). Thus this interpretation is based only on kinematic features of the observed phases.
3. The interpretation of phase P3 as the bottom-reflected wave and P4 as the surface-bottom reflection provide a rather different estimate of the sea depth ***H***=212 m. This interpretation is based on both kinematic and dynamic features of the observed waves, but is in disagreement with the batymetric map (another discrepancy is that surface-bottom reflection should be negative due to reflection from the water surface). The difference can not be related to estimation errors, and at the moment we can not provide any reasonable explanation and make a choice between the two interpretations.
4. The bubble period was estimated as the average time interval between the 1st and 2nd bubble pulses.
5. The distance values are very close to the preliminary estimations (Progress Report No. 26, 1999). A little increased charge depth estimation ***h***=73.5 m for the 5000 kg shot seems to be reasonable, possibly due to long-drown rope and a charge-center shift.

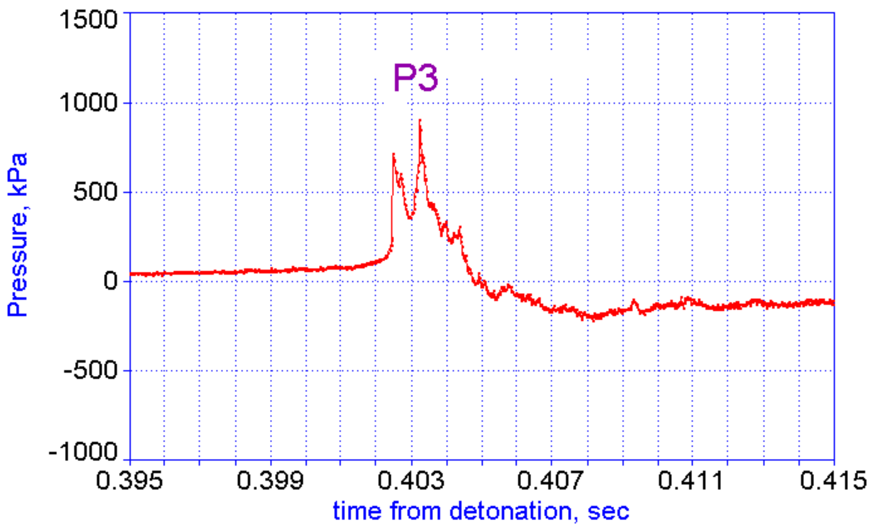

Fig. 6. Complex form of the P3 phase for the shot 5000 kg.

Obtained estimates of the shot configuration parameters and the bubble period are presented in Table 3.

Table 3. Shot configuration parameters and bubble periods estimated from shock wave travel times.

Charge, kg	Shot depth ***h***, m	Sea depth, ***H***, m	Hypocentral distance ***r***, m	Bubble period T_b, sec	Comments
500	-	-	900	0.390	no precise piezoelectric measurements
2060	70	-	770, 795	0.578	***r*** is for two gages separated by 25 m
5000	73.5	265 (or 212)	618	0.782	***H*** estimate depends on phase interpretation

6. Enhanced peak pressures. For the largest shot of 5000 kg, the main blasting agent CHEN AMON was about 97% of the total charge weight (see Table 1). According to the manufacturer estimation the explosive energy is about 80% of TNT. Nevertheless, the measured peak pressures significantly exceeded the expected values from an equal TNT charge in ocean water (see Table 4, Fig. 7).

USACE (1991) and Joachim and Welch (1997), in a form similar to that provided by Cole (1948), give the relationships:

$$P(t) = P_m\, e^{-(t-ta)/Q} \quad (2)$$

$$P_m\,(MPa) = 53.1\,(W^{1/3}_{(kg)}/R_{(m)})^{1.13} \quad (3)$$

$$t_a = r/C_w \quad (4)$$

$$Q_{(s)} = 9.2{*}10^{-5}\, W^{1/3}\, R_s^{0.18} \quad (5)$$

$$R_s\,(m/kq^{1/3}) = r/W^{1/3} \quad (6)$$

where P_m is the peak pressure, t_a is the arrival time, Q is the time constant, W is the equivalent weight, in kg, of TNT, detonated in ocean/lake water, r is the lateral distance in m, C_w is the sonic velocity in water, m/sec.

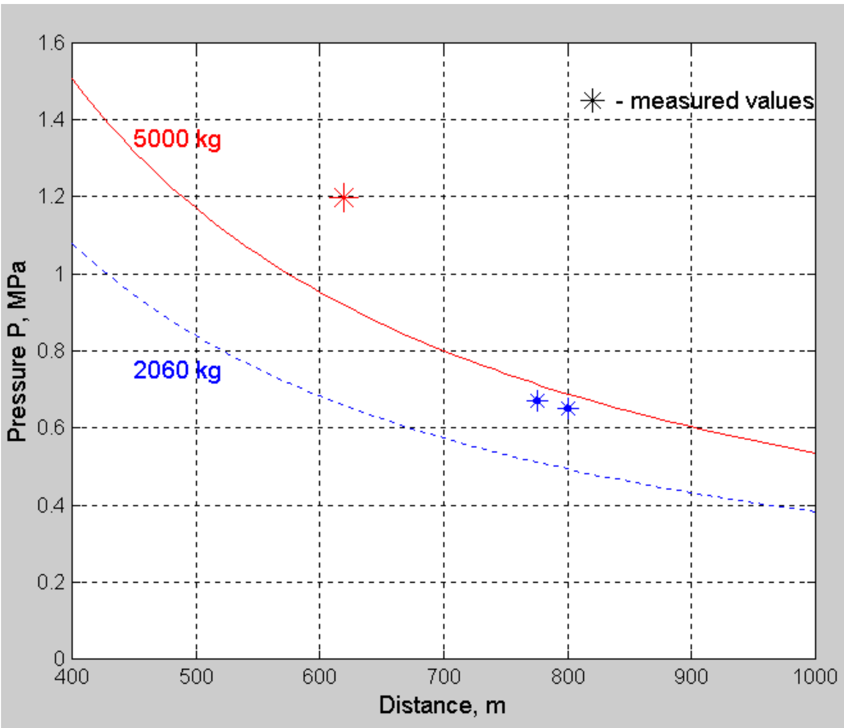

Fig. 7. Peak water pressure vs distance for underwater explosions of TNT in the ocean water and measurements of the Dead Sea shots.

The peak pressure values in Table 4 and Fig. 7 are calculated by Eq. 3. This observation of the enhanced pressures for the Dead Sea shots can be attributed to the acoustic impedance of the supersaline Dead Sea water being about 40% higher than in the ocean and, thus, yielding a much stronger shock waves impact (see also Eq. 7).

Table 4. Parameters of the shock waves for the explosions on 10.11.99 and 11.11.99.

Explosive weight, kg	Distance R, m	Sensor depth, m	Peak pressure, kPa		
			Estimated from eq.(3)	Measured	Ratio measured/estimated
2060	770	30	515	672	1.30
	795	25	496	654	1.32

5000	618	30	922	1230	1.33

7. Estimation of the shock wave energy. Shock wave energy flux density is calculated as (Cole, 1948):

$$E_{DS} = Z_{DS}^{-1}\int P^2(t)dt \qquad (7)$$

where Z_{DS} is the Dead Sea water acoustic impedance, $Z_{DS}=\rho_{DS}*C_{DS}$ =1236kg/m$^3\times$1770m/sec, and P(t) is the curve-fit equation (see Fig. 8) with estimated time constant Q_{DS} = 0.0018458 sec:

$$P_{DS}(t) = 1.23*\exp[-(t-0.3592)/Q_{DS}] \quad \text{(in MPa)} \qquad (8)$$

Integral in (7) is calculated from the arrival time t_a=0.3592 sec to $t=t_a+6.7Q$ (Cole, 1948).

The full shock wave energy can be calculated (at distance r=618 m) as:

$$E_{DS} = \frac{1}{Zw}\int_{t_a}^{t_a+6.7Q}(10^3\times 1230\times\exp(-(t-0.3592)/Q))^2\,dt = 1219\ joul/m^2$$

$$E_s = E_{DS}\times 4\pi r^2 = 0.585\times 10^{17}\ \text{erg}$$

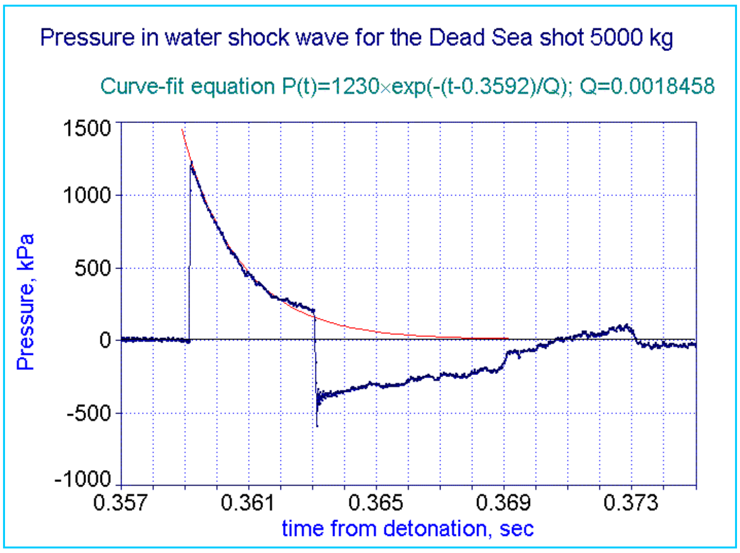

Fig.8. Primary and surface-reflected shock waves and the curve-fit equation.

Specific energy of the explosive CHEN AMON, used in the experiment, according to the manufacturer specifications: 1000 cal/gr = 4.2$\times$10^{13} erg/kg, and the full explosive energy is: E_e=2.1$\times$10^{17} erg. Then the share energy estimate for the primary shock wave is estimated to be

$$E_s/E_e = 27.5\%$$

8. Preliminary estimation of the TNT equivalent. It is assumed that the primary shock wave energy flux for the Dead Sea shot (W=5000 kg of CHEN AMON) E_{DS} equals the shock wave energy flux E_{OC} for the "equivalent" TNT charge W_T exploded in the ocean water:

$$E_{DS} = E_{OC} \qquad (9)$$

The value E_{OC} is calculated from Eq. (3,5,7):

$$E_{OC} = Z_{OC}^{-1}\int[53.1(W_T^{1/3}/r)^{1.13}\exp(-t/Q_{OC})]^2dt \qquad (10)$$

where the impedance for the ocean water is Z_{OC}=1030kg/m^{3*}1536m/sec, and Q_{OC} depends on $W_{T,}$ as in Eq. (5). The value E_{DS} is calculated from Eq. (7,8):

$$E_{DS} = Z_{DS}^{-1}\int[1.23*\exp(-t/Q_{DS})]^2dt \qquad (11)$$

Finally, the TNT equivalent to the 5000 kg charge of CHEN AMON exploded in the Dead Sea is determined from Eq.(9-11) as:

$$W_T = 4010 \text{ kg}$$

This value corresponds to the manufacturer estimation of the explosive CHEN AMON energy as about 80% of TNT.

CONCLUSIONS AND RECOMMENDATIONS

The video and audio tracks present interesting phenomena such as the “cavitation hat”, arrivals of the shock waves and the bubble pulsations at the raft, and water uplift at the detonation point. The video clips also provid a rough estimation of the shock wave propagation time to the surface and to the raft and contribut to verification of the charge depth and explosion-to-raft distance.

The measured peak pressures significantly exceed the expected values from an equal TNT charge in ocean water due to enhanced acoustic impedance of the super saline Dead Sea water. Analysis of different phases and arrival times on the records enables the identification of surface (“ghost”) and bottom reflections and contributed to the verification of the experiment configuration. The shock wave energy was calculated utilizing the wave energy flux density equation, recorded pressure-time functions specific for the Dead Sea water. These observations could also provide preliminary estimations of the shock energy share relative to the explosive energy, and TNT equivalent of the shots.

This is not the first time that explosions have been carried out in the Dead Sea; it is, however, the first time that a seismic source with an equivalent magnitude of about 4.0 on the Richter scale has been artificially generated in the area. The experiment is also unique for this region since it has precise source information of a seismic event that was recorded over 2500 km beyond the borders of Israel.

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